United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

NIST Special Publication 919

International Workshop on Fire Performance of High-Strength Concrete, NIST, Gaithersburg, MD, February 13-14, 1997 Proceedings

Long T. Phan, Nicholas J. Carino, Dat Duthinh, and Edward Garboczi

B.4 STUDIES ON THE FIRE RESISTANCE OF HIGH-STRENGTH CONCRETE AT THE NATIONAL RESEARCH COUNCIL OF CANADA

V.K.R. Kodur
National Fire Laboratory
Institute for Research in Construction
National Research Council of Canada

ABSTRACT

High-strength concrete has been utilized in many high-rise buildings and its major application is in columns. With the increased use of high-strength concrete in columns, concern has developed regarding its behaviour in fire, in particular, the occurrence of spalling at elevated temperatures. Studies are in progress at the National Research Council of Canada to develop fire resistance design guidelines for high-strength concrete for incorporation in codes and standards. The studies are focussed on conducting full scale fire tests on structural members, establishing material properties at high temperatures, and in developing numerical models to evaluate the performance of HSC structural members. An overview of the current research studies on high-strength concrete columns is outlined in this paper.

Keywords: high-strength concrete, fire resistance design, high temperature behaviour, concrete-filled steel columns, reinforced columns, spalling, material properties

1. INTRODUCTION

In recent years, the construction industry has shown significant interest in the use of high-strength concrete (HSC). This is due to the improvements in structural performance, such as high-strength and durability, that it can provide compared with traditional concrete. In Canada, high-strength concrete is being used in many applications such as bridges, offshore structures and infrastructure projects. In recent years, its use has been extended to high rise buildings as well. One of the major uses of HSC in buildings is in columns.

In Canada, the specifications for fire resistance requirements for structural members are contained in the National Building Code of Canada (NBCC) (1). Concrete structures in Canada are to be designed in accordance with the CSA A23.3-M94 standard (2). The most recent edition of this standard contains detailed specifications on the design of HSC structural members, however, there are no guidelines on the fire resistance design of HSC structural members either in CSA A23.3-M94 or in the NBCC.

The results of fire tests in a number of laboratories (3, 4) have shown that there are well-defined differences between the properties of HSC and normal strength concrete at high temperatures. Further, concern has developed regarding the occurrence of explosive spalling when HSC is subjected to rapid heating, as in the case of a fire (3, 5).

Studies are in progress at the National Research Council of Canada (NRC) to develop fire resistance design guidelines for the use of high-strength concrete for possible incorporation in codes and standards. The main objective of this research, being undertaken in partnership with industry, is to study the behaviour of HSC at elevated temperatures and to develop solutions to minimize spalling and to enhance its fire resistance. In this paper, an overview of the current research program being undertaken at NRC is outlined.

2. FIRE RESISTANCE OF HIGH-STRENGTH CONCRETE

In buildings, HSC structural members are to be designed to satisfy the requirements of serviceability and safety limit states. One of the major safety requirements in building design is the provision of appropriate fire safety measures for structural members. The basis for this requirement can be attributed to the fact that, when other measures for containing the fire fail, structural integrity is the last line of defence.

The fire safety measures for structural members are measured by means of fire resistance. Fire resistance is defined as the ability of a structural element to maintain its load-bearing function under fire conditions. It is the time during which a structural member exhibits resistance with respect to structural integrity, stability and temperature transmission. Fire resistance of a structural member is dependent on the geometry, the materials used in construction, the load intensity and the fire characteristics.

In the case of HSC, the spalling of concrete under fire conditions is one of the major concerns due to the low water-cement ratio in HSC. The spalling of concrete exposed to fire has been observed in concrete structural members under laboratory and real fire conditions (5, 6). Spalling, which results in the loss of concrete during a fire, has the effect of exposing deeper layers of concrete to fire temperatures, thereby increasing the rate of transmission of heat to the inner layers of the structure, including to the reinforcement.

Spalling is theorized to be caused by the build up of pore pressure during heating (3, 7). HSC is believed to be more susceptible to this pressure build up because of its low permeability compared to normal strength concrete. The extremely high water vapour pressure, generated during exposure to fire, cannot escape due to the high density of high-strength concrete and this pressure often reaches the saturation vapour pressure. At 300°C, the pressure reaches about 8 MPa. Such internal pressures are too high to be resisted by the HSC mix having a tensile strength of about 5 MPa (5).

Data from various studies (3, 4, 5) show that spalling of HSC is affected by the following factors:

- original compressive strength
- moisture content of concrete
- concrete density
- heating rate
- specimen dimensions and shapes
- loading conditions

Preliminary studies indicated that the addition of polymeric fibre reinforcement to concrete reduces spalling (3, 6, 8). Experimental studies on high-strength reinforced concrete columns showed deep spalling and rupture after fire tests, however, only slight or no spalling was observed in fire tests on thc same HSC columns reinforced with polypropylene fibres (6). The occurrence of spalling, as well as the extent of spalling, varied from one study to the other thus presenting a confusing picture on the behaviour of HSC at elevated temperatures (5).

3. STUDIES AT NRC

Studies are in progress at NRC to develop fire resistance design guidelines for HSC for possible incorporation in codes and standards. The main objective of this research, being undertaken together with the Portland Cement Association, Canadian Portland Cement Association, Concrete Canada, and National Chiao Tung University (NCTU), Taiwan, is to study the behaviour of HSC at elevated temperatures and to develop solutions to minimize spalling. Both experimental and theoretical studies are being carried out to study the behaviour of HSC structural elements and to establish the material properties of HSC at elevated temperatures.

3.1 Element Tests

The experimental studies are focussed on two types of structural elements; namely HSC-filled steel columns and HSC columns.

3.1.1 <u>HSC-Filled Steel Columns</u>

Steel hollow structural section (HSS) columns are very efficient structurally in resisting compression loads and are widely used in the construction of framed structures in industrial buildings. HSS columns, on their own, have a fire resistance of 20 to 30 minutes and need to be provided with additional measures to obtain the required fire resistance, as specified in building codes.

HSS columns are often filled with concrete in order to achieve increased load-bearing capacity. Concrete filling of HSS sections increases fire resistance. In order to quantify the fire resistance from concrete filling, studies were undertaken on three types of concrete-filled HSS columns; namely plain concrete, reinforced concrete and steel fibre-reinforced concrete. Both normal strength concrete (NSC) and HSC were considered. Detailed results on NSC-filled HSS columns are given in Reference (9) while the results of HSC-filled columns are discussed in Reference (4). In this paper, only the comparative performance of HSC-filled and NSC-filled HSS columns are discussed by considering four HSS columns; namely, two columns filled with NSC (NSC1 and NSC2), a column filled with HSC (HSC1) and a column filled with fibre-reinforced high-strength concrete (HFC1).

Figure 1 shows elevation and cross-sectional details for the four HSS columns used in the experimental studies. All columns were 3810 mm long and were of circular cross section. The 28-day compressive strength of concrete for NSC was approximately 40 Mpa, while for HSC it was approximately 90 MPa.

The comparative performance of NSC- and HSC-filled HSS columns under fire conditions is illustrated in Figure 2. The variation of the axial deformation with time is compared for the NSC- and HSC-filling (Columns NSC2 and HSC1). These two columns had similar characteristics and were subjected to similar load levels (4). As expected, the columns expanded in the initial stages, and most of the load was supported by the steel section, then contracted leading to failure. In the range where the steel section was carrying the load, the behaviour of the two columns was similar.

At increased temperatures, the steel section gradually yielded because of decreasing strength, and the column contracted. At this stage, the infilled concrete started to take over the load and carried a progressively increasing portion of the load with increasing temperature. The strength of the concrete also decreased with time and, ultimately, when the column could no longer support the load, failure occurred. In this region, the behaviour was dependent on the type of concrete filling. The failure of the HSC-filled HSS column occurs by sudden contraction, while the failure of the NSC-filled HSS column occurs by gradual contraction. In these tests, the time to reach failure is defined as fire resistance. For the NSC-filled HSS column, the fire resistance was approximately 150 minutes while, for the HSC-filled HSS column, it was only approximately 45 minutes.

The comparative performance of HSS columns filled with NSC (NSC1) and HFC (HFC1) under fire conditions is shown in Figure 3. The variation of the axial deformation with time is compared for the two columns. These two columns had similar characteristics and were subjected to similar load levels (4). The deformation behaviour of the fiber-reinforced high-strength concrete-filled steel column, HFC1, was similar, during the early stages of the test, to that of the normal strength concrete-filled steel Column NSC1. After approximately 40 minutes, Column HFC1 performed better than Column NSC1 since the presence of steel fibres enhanced ductility. While the lower load intensity on Column HFC1 contributed to an increased fire resistance to some extent, much of the contribution is from the presence of steel fibres and the high-strength concrete.

This can be attributed to the superior mechanical properties of steel fibre-reinforced concrete. There is very little information on the properties of steel fibre-reinforced high-strength concrete, however, studies on steel fibre-reinforced normal strength concrete (8, 9) have shown that the compressive strength increases with temperature up to about 400°C.

3.1.2 Reinforced Concrete Columns

As part of an experimental study, forty-eight full-scale reinforced concrete columns are being tested by exposing the columns to fire under structural loads. These columns are made with two types of HSC, namely plain-HSC and fibre-reinforced-HSC. Both polypropylene and steel fibres are being considered in the study. Twenty columns with plain-HSC, eight columns with steel fibre-reinforced-HSC and twenty columns with polypropylene fibre-reinforced-HSC are being fabricated.

All columns are 3810 mm long and are of either square or rectangular cross section. Two sizes of square columns, 306 mm and 406 mm, are being considered in the study. The rectangular columns are 306 x 456 mm and 203 x 916 mm. The test variables are column section dimensions, tie spacing, load intensity, end conditions, concrete strength, aggregate type and reinforcement. Figure 4 shows elevation and cross-sectional details for a typical column considered in the study. Further details on the columns are given by Kodur (8).

The construction of the columns with plain-HSC and with steel fibre-reinforced-HSC is complete. The polypropylene fibre-reinforced concrete columns are expected to be constructed shortly. Two types of coarse aggregate, namely, siliceous aggregate and carbonate aggregate, are being used in the concrete mix to study the influence of aggregate on the fire performance of HSC. The compressive strengths of the concretes are in the range of 80-90 MPa.

The tests will be carried out by exposing the HSC columns to heat in a furnace specially built for testing loaded columns. The test furnace, shown in Figure 5, is designed to produce conditions such as temperature, structural loads and heat transfer, to which a member might be exposed during a fire. It consists of a steel framework with the furnace chamber inside it. The furnace facility includes a hydraulic loading system with a capacity of 1,000 t.

The columns will be tested under the maximum allowable load according to North American Building Codes for concrete structures (2, 10). Most of the HSC columns will be subjected to constant concentric loads during testing. However, some columns will be tested under eccentric loads to study the influence of eccentricity on the performance of columns at high temperatures.

During the test, the column will be exposed, under a load, to heating controlled in such a way that the average temperature in the furnace follows, as closely as possible, the ASTM E119-88 (11) standard temperature-time curve. The furnace, concrete and steel temperatures, as well as the axial deformations and rotations, will be recorded until failure of the column.

3.2 Material Properties

Results from the fire tests will be used to develop computer models for predicting the behaviour of HSC columns exposed to fire. For use in these computer programs, the thermal, mechanical and deformation properties of HSC at elevated temperatures are needed. To establish these properties, a study is being carried out as part of a joint research project involving NRC and NCTU.

The thermal properties that are being studied are thermal conductivity, specific heat and the mass loss of the concretes. The mechanical properties that are being investigated are the compressive strength, tensile strength, modulus of elasticity and ultimate strain. The deformation properties being studied are the thermal expansion and creep.

HSC, with and without fibres, is being considered in this study. Experimental studies on thermal and deformation properties are being carried out at NRC while tests on mechanical properties are being carried out at NCTU. Two types of concrete specimens will be investigated in the study. The first one is plain concrete and the second one is steel fibre-reinforced concrete. Both concrete types will be made with siliceous and carbonate aggregates. The 28-day compressive strength of concrete will be about 90 MPa.

The data obtained from the studies will be used to develop thermal and mechanical relationships, as a function of temperature, for HSC. These relationships can be used as input in computer programs to determine the behaviour of HSC structural members at high temperatures (12).

3.3 Numerical Studies

The development of computer programs for predicting the fire behaviour of HSC columns is currently in progress at NRC (13). The steps, associated with the development of the models, involve the calculation of the fire temperatures, the cross-sectional temperatures, and the evaluation of the deformations and strength of an HSC column. The effect of spalling will be accounted for through pore pressure computations. The validity of the computer programs will be established by comparing the predictions from the computer programs to test data.

The computer programs will then be used to carry out detailed parametric studies of the influences of the various parameters, such as concrete strength and load intensity on the fire resistance of HSC columns. Data from the parametric studies will be used to develop design guidelines to overcome the problem of spalling in HSC columns and for predicting the fire resistance of HSC columns.

4. SUMMARY

An overview of the current research program on high-strength concrete columns is outlined in this paper. Based on the studies completed so far, it was found that:

- The behaviour of HSC-filled steel columns at high temperatures is significantly different from that of NSC-filled HSS columns.
- The fire resistance rating of HSC-filled HSS columns can be significantly improved by adding steel fibre reinforcement to concrete.

The studies, currently in progress at NRC, will generate data on the fire resistance of HSC columns and contribute to identifying the conditions under which these columns can be safely used.

5. ACKNOWLEDGEMENTS

The research described in this paper is the result of partnerships between the National Research Council of Canada and the Canadian Steel Construction Council, Portland Cement Association, Canadian Portland Cement Association, Concrete Canada and the National Chiao Tung University in Taiwan.

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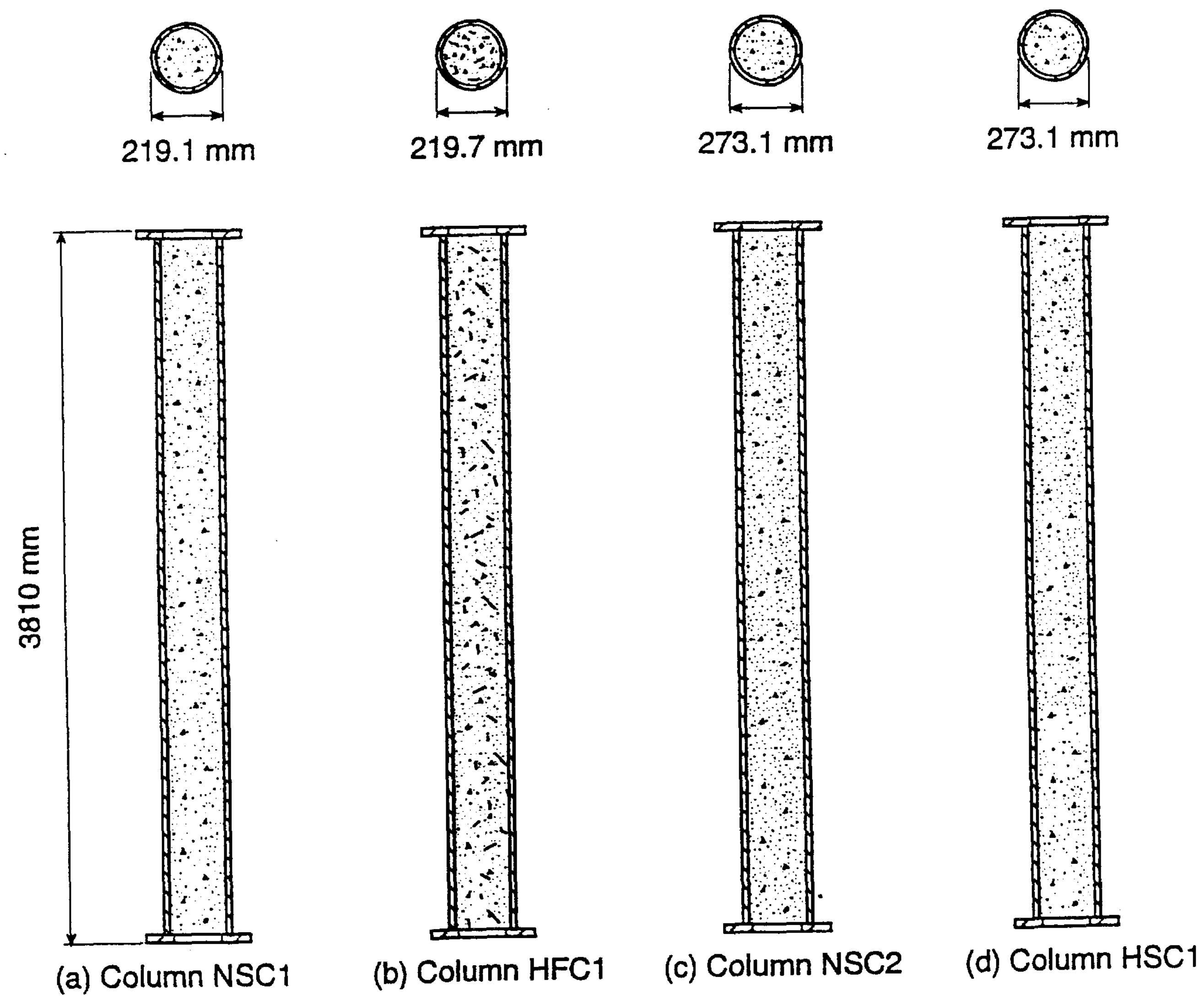

Figure 1 Elevation and Cross Section of Columns

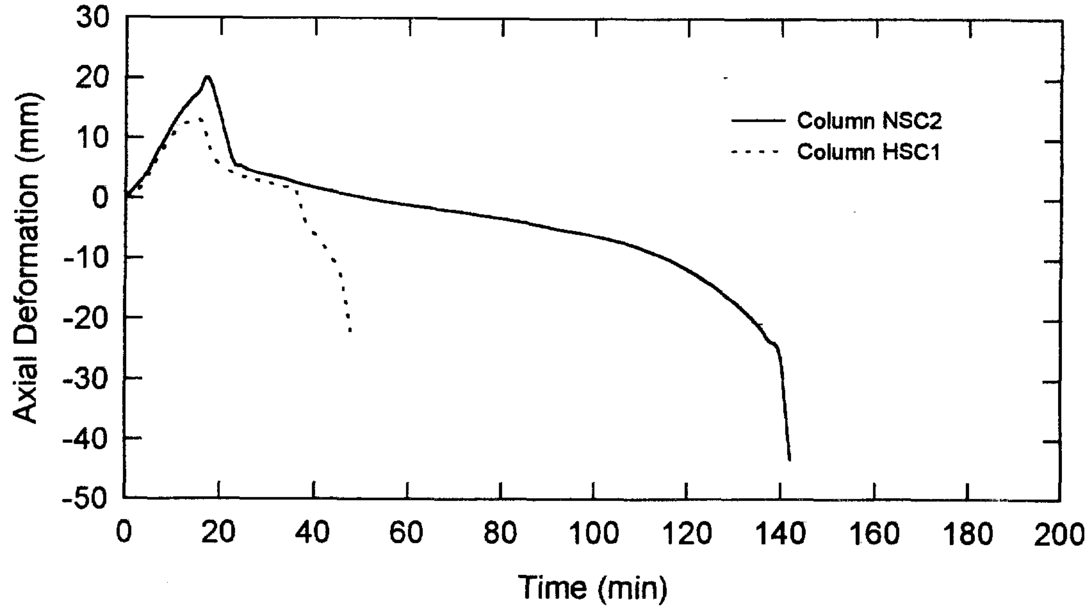

Figure 2. Axial deformations of Columns NSC2 and HSC1 as a function of exposure time

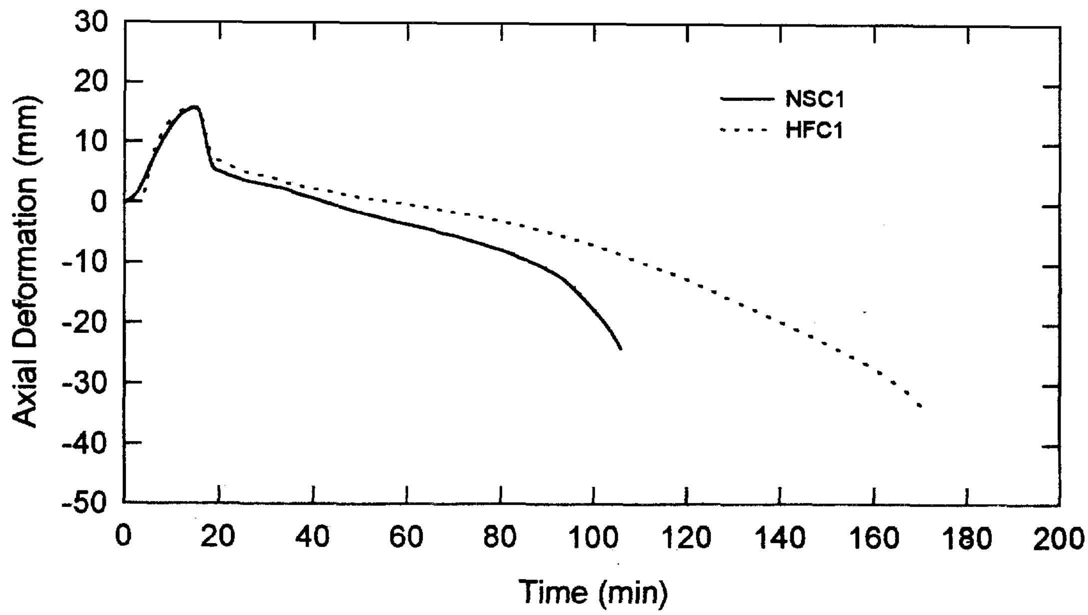

Figure 3. Axial deformations of Columns NSC1 and HFC1 as a function of exposure time.

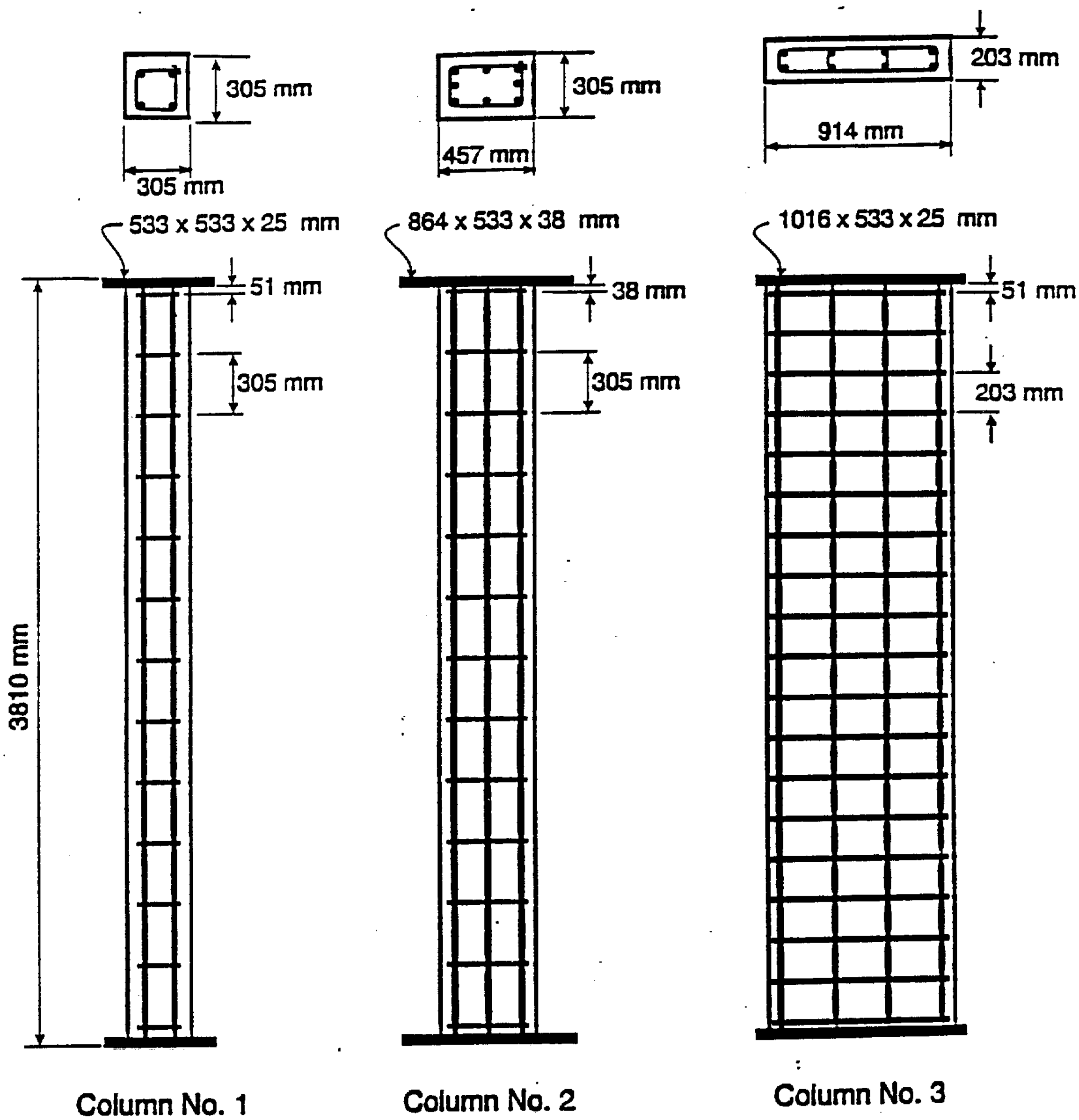

Figure 4 RC Columns Layout

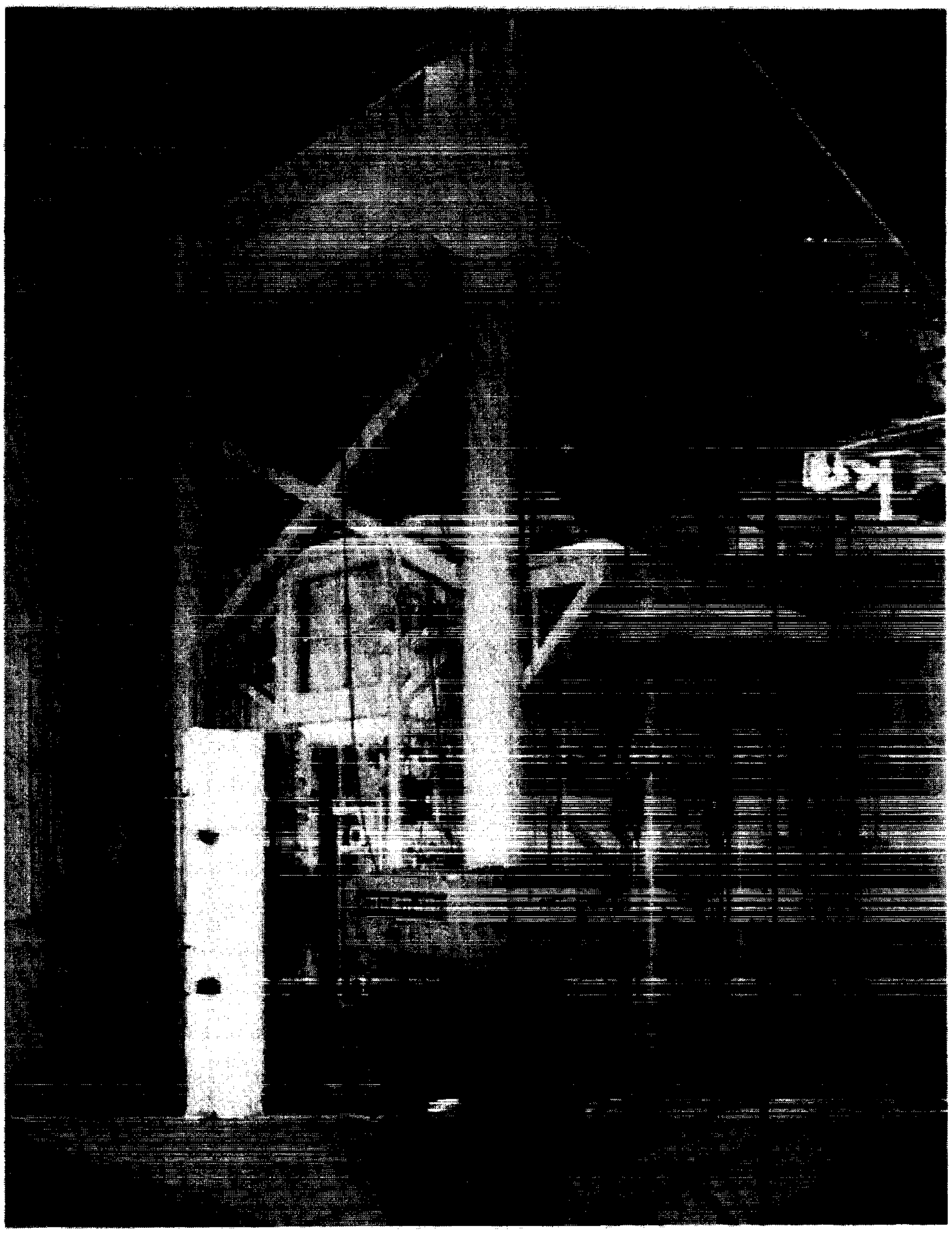

Figure 5 Column Test Furnace